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# Dilution effects on laminar jet diffusion flame lengths

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# Abstract

Many studies have examined the stoichiometric lengths of laminar gas jet diffusion flames. However, these have emphasized normal flames of undiluted fuel burning in air. Many questions remain about the effects of fuel dilution, oxygen-enhanced combustion, and inverse flames. Thus, the stoichiometric lengths of 287 normal and inverse gas jet flames are measured for a broad range of nitrogen dilution. The fuels are methane and propane and the ambient pressure is atmospheric. Nitrogen addition to the fuel and/or oxidizer is found to increase the stoichiometric lengths of both normal and inverse diffusion flames, but this effect is small at high reactant mole fraction. This counters previous assertions that inert addition to the fuel stream has a negligible effect on the lengths of normal diffusion flames. The analytical model of Roper is extended to these conditions by specifying the characteristic temperature that scales with the adiabatic flame temperature and the ambient temperature. The extended model correlates the measured lengths of normal and inverse flames with coefficients of determination of 0.87 for methane and 0.97 for propane.

Keywords: Flame shape; Inverse flames; Oxygen enrichment; Roper model

#### 1. Introduction

Laminar gas jet diffusion flames have been widely studied for both fundamental and practical reasons. To design burners and experiments, and to validate numerical models, it is helpful to understand the stoichiometric length behavior of these flames [1–7]. The burning of diluted fuels in ambients other than air has applications to exhaust-gas recirculation combustors, oxygen-enhanced combustion, and fire safety [5,8–13].

The effects of reactant dilution on stoichiometric lengths ( $L_{st}$ ) of normal diffusion flames (NDFs) are not fully understood. McEnally and Pfefferle [2] found  $L_{st}$  increased monotonically as diluent was added to the fuel. In contrast, some experimental [14] and modeling [14,15] studies found  $L_{st}$  to be independent of diluent addition to the fuel. Oxidizer dilution was experimentally found to increase  $L_{st}$  [5]. None of these studies considered highly diluted fuels or oxygen enrichment.

Schug et al. [8] concluded from their experiments that "flame height ... is strictly proportional to the volumetric fuel flow rate and not to the total rate of fuel plus additive." This claim was also published in other papers co-authored by

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Fig. 1. (a) Color image of the test apparatus. (b) Schematic of the IDF tests. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Glassman. However, the flame heights measured in Ref. [8] were luminous lengths of sooty flames. Furthermore, subsequent experiments found inert addition could either reduce [16] or increase [17,18] luminous flame lengths.

Inverse diffusion flames (IDFs), where the oxidizer is surrounded by fuel, are less common in research and in applications. However, they are equally important from a fundamental perspective and can be studied with many of the same diagnostics, theories, and numerical models [19–22]. To date the greatest research interest in IDFs has involved their soot formation behavior [23–25] and shapes [6,22,26–29]. Little has been published concerning the effects of dilution on the lengths of IDFs. Two experimental studies [6,7] found the  $L_{sr}$ for IDFs to increase when nitrogen was added to the oxidizer, and Lee et al. [3] found it to increase with fuel stream dilution. All three studies involved a small range of dilution.

The analytical model of Roper [30,31] has been used to predict  $L_{st}$  of NDFs [5,28,32] and IDFs [6,27,28] with various burner geometries and fuels. Although these have been generally successful, no attempt has been made to apply the Roper model to NDFs and IDFs across a wide range of dilution conditions.

In this study, the  $L_{st}$  of normal and inverse steady laminar gas jet diffusion flames are measured. The fuels are methane and propane and the inert is nitrogen. A wide range of dilution is considered for both the fuel and the oxidizer. The Roper model is extended to these conditions, allowing for proper consideration of gas properties, and the results are compared with the measurements.

# 2. Experimental

Tests were performed using a co-flow burner and chimney, as shown in Fig. 1a. The burner's inner port was stainless steel with an inside diameter of 2.9 mm, an outside diameter of 4.2 mm, and a blunt tip. The outer tube was brass with a diameter of 102 mm and its flow was conditioned with a ceramic honeycomb. The glass chimney was 155 mm long with an inside diameter of 100 mm. The top of the chimney was sealed with aluminum foil with a 15 mm round hole on axis. Ignition was accomplished with a NiCr wire, which was withdrawn after ignition. For IDFs, a secondary flame was ignited above the chimney, as shown in Fig. 1b, to eliminate unburned fuel. This flame had no effect on the primary flame inside the chimney.

The gases were CH<sub>4</sub> (99.99%), C<sub>3</sub>H<sub>8</sub> (99.5%), O<sub>2</sub> (99.994%), and N<sub>2</sub> (99.998%). Ambient conditions were 1.01 bar and 25 °C. The gas flow rates were controlled with metering valves and measured with calibrated rotameters. Uncertainties in the flow rates are estimated at  $\pm$  5%. The reactant and nitrogen flow rates were varied as widely as possible. Such variation was limited by flames shorter than 6 mm, flames whose tips approached the top of the chimney, flames that were lifted more than 1 mm, flames that flickered, and flames with too much soot to reasonably identify where the blue



Fig. 2. Stoichiometric flame lengths for methane predicted by the Roper model, Eq. (1), in terms of burner reactant mole fraction for (a) NDFs and (b) IDFs. For these plots  $T_f = 1500$  K,  $T_0 = 293$  K, and  $D_0 = 20$  mm<sup>2</sup>/s.

flame zone crosses the flame axis. The ambient reactant flow rate was maintained at a minimum of five times stoichiometric and the flame height was found to be independent of ambient gas flow rate.

The flames were imaged with a digital color camera (Nikon D100). Shutter times (0.66–300 ms) were selected such that the brightest region in each image was slightly below saturation. The front of the lens was 40 cm from the flame axis and the optical axis was 50 mm above the burner port. To avoid gamma corrections, flame images were saved in uncompressed Nikon-specific format, and converted to tif format by Dcraw. With the exceptions of "-4" and "- T," only default settings were used. ImageJ was used to obtain the red, green, and blue (RGB) intensities, from which grayscales were calculated as their average. Stoichiometric flame lengths were defined as the height above the burner tip of the highest grayscale intensity along the axis [5,27]. This agreed with visual determinations based on the center of the blue flame zone. Uncertainties in the measured  $L_{st}$  are estimated at  $\pm 10\%$ . Several flames were imaged with a CH filter in front of the camera, but this complicated differentiating between blue and yellow emissions.

#### 3. Analytical

Roper [30] developed an analytical model of mixture fraction distribution in steady laminar gas jet diffusion flames. His key assumptions were those of: equidiffusion of momentum, heat and mass (Sc = Le = 1); negligible axial diffusion; constant temperature and diffusivity near the reaction zone; and equal moles of reactants and products. This model predicts that the stoichiometric length of a

diffusion flame on a circular burner is given by

$$L_{st,Roper}/Q = [4\pi D_o \ln (1 + 1 / S)]^{-1} (T_o / T_f)^{0.67},$$
(1)

where  $D_o$  is the characteristic diffusivity of the gas mixture at ambient temperature  $T_0$ ; Q is the volumetric flow rate of the burner gas (at ambient conditions); S is the ratio of the volume of ambient gas to the volume of burner gas for stoichiometric combustion; and  $T_f$  is the characteristic temperature for mass diffusion. As examples, methane NDFs and IDFs have  $S = 2 X_{CH_4}/X_{O_2}$  and the inverse of this, where X is the reactant mole fraction in the supply stream.

Roper et al. [31] calibrated Eq. (1) using measured lengths of approximately 64 NDFs burning various fuels, nearly all of them in air. These lengths were determined from measurements of CO and soot concentrations, which may not accurately represent stoichiometric flame lengths. This calibration yielded  $T_f = 1500$  K and  $D_o = 20$  mm<sup>2</sup>/s (which is the binary diffusivity of O<sub>2</sub> into N<sub>2</sub> at 293 K).

Figure 2 illustrates the effects of inert addition on the  $L_{st}$  predicted by Eq. (1) for methane NDFs and IDFs. These plots include  $Q_{CH_4}$  and  $Q_{O_2}$ , defined as  $Q_{CH_4} = Q X_{CH_4}$  and  $Q_{O_2} = Q X_{O_2}$ . As shown in Fig. 2, Roper's theory predicts that  $L_{st}$ increases with inert addition to the burner and/or ambient gas for both NDFs and IDFs. However, this effect is small for high reactant mole fraction. For example, a methane/air NDF will have a small length increase when the fuel is diluted (at constant methane flow rate) and a large length increase when the air is diluted. As shown by Ref. [5], the trends seen in Fig. 2 are also predicted by the analytical models of Altenkirch, Spalding, and Villermaux. These trends are counter to past claims that inert



Fig. 3. Representative methane flame images and intensity profiles, in arbitrary units. (a) An NDF with  $\dot{m}_{CH_4} = 2.93$  mg/s,  $X_{O_2} = 1$ , and  $X_{CH_4} = 0.23$ . (b) An IDF with  $\dot{m}_{O_2} = 6.77$  mg/s,  $X_{CH_4} = 0.29$ , and  $X_{O_2} = 0.82$ .

Table 1

Binary gas diffusivity  $D_{k-j}$  (mm<sup>2</sup>/s) of species k into species j at 1.01 bar and 298 K, found from the Lennard-Jones potential equation using the gas properties of Reid et al. [34].

		Species j		
		$N_2$	CO <sub>2</sub>	H <sub>2</sub> O
Species k	$\begin{array}{c} CH_4\\ C_3H_8\\ O_2 \end{array}$	21.9 11.3 20.4	16.6 8.0 15.2	14.9 9.7 21.0

addition to the burner gas has a negligible effect on stoichiometric flame length [14,15]. These studies involved burner gas mole fractions of 0.4 - 1, which may have been too high for a significant effect (see Fig. 2).

The above values for  $T_f$  and  $D_0$  do not fully account for changes that occur when the reactants, diluents, or dilution levels change significantly. Thus the Roper model is extended here by considering more robust definitions of  $T_f$  and  $D_0$ . For this it is assumed that the characteristic diffusivity in gas jet diffusion flames is that of reactants (here  $O_2$  and  $CH_4$  or  $C_3H_8$ ) into the stoichiometric products (here  $H_2O$ ,  $CO_2$ , and  $N_2$ ). The mass diffusivity of reactant *k* into the product mixture is [33]:

$$D_{k-prods} = \frac{1 - X_k}{\sum_{j=1}^3 X_j / D_{k-j}},$$
(2)

where  $D_{k-j}$  is the binary diffusivity of species k and j. The individual binary diffusivities are shown in Table 1.

It is further assumed that the fuel and oxidizer contribute equally to the characteristic mass diffusivity, i.e.,

$$D_0 = 0.5 \left( D_{\text{fuel-prods}} + D_{\text{O}_2 - \text{prods}} \right) \tag{3}$$

This differs from previous studies of NDF lengths where either fuel diffusivity [1,35] or oxidizer diffusivity [31] was assumed to control  $L_{st}$ .

Following past work [27,28], the characteristic temperature for mass diffusion in diffusion flames is assumed to be

$$T_f = T_0 + \alpha (T_{ad} - T_0), \tag{4}$$

where  $T_{ad}$  is adiabatic flame temperature and  $\alpha$  is an empirical factor to be found below. This is the only calibration factor in this extension of the Roper model.

#### 4. Results and discussion

Figure 3 shows representative images of an NDF and an IDF. The NDF has a thin blue flame sheet surrounded by blue haze and has no visible soot. The IDF has a much thicker blue stoichiometric contour and yellow soot is visible outside and above this. RGB and greyscale intensity profiles along the axis are plotted. For each flame, the four profiles reach their peaks at the same height.

Figure 4 demonstrates the effects of nitrogen addition to the burner gas. Figure 4a shows a sequence of representative NDFs with constant methane mass flow rate ( $\dot{m}_{CH_4}$ ) and  $X_{O_2}$ . At constant  $\dot{m}_{CH_4}$ , the stoichiometric flame length increases with nitrogen addition to the fuel, in agreement with the observations of McEnally and Pfefferle [2]. Figure 4b presents a sequence of representative IDFs with constant  $\dot{m}_{O_2}$  and  $X_{CH_4}$ . Again,  $L_{st}$  increases with nitrogen addition to the burner gas when the burner reactant flow rate is constant. Consistent with Fig. 2, these increases in  $L_{st}$  diminish with increasing burner reactant mole fraction.

A total of 174 NDFs and 113 IDFs were observed, as summarized in Fig. 5 and Table 2. The conditions sought to include the broadest possible range of reactant mole fractions, adiabatic



Fig. 4. Color images of representative methane diffusion flames. (a) shows NDFs ( $\dot{m}_{CH_4} = 2.97 \text{ mg/s}$  and  $X_{O_2} = 0.5$ ) and (b) shows IDFs ( $\dot{m}_{O_2} = 6.77 \text{ mg/s}$  and  $X_{CH_4} = 0.48$ ). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).



Fig. 5. Test matrix of (a) methane and (b) propane jet diffusion flames. The dashed curves denote constant  $T_{ad}$ .

Table 2	
Summary of the test matrix.	

	CH <sub>4</sub>		C <sub>3</sub> H <sub>8</sub>	
	NDF	IDF	NDF	IDF
Number of flames	152	96	22	17
$X_{\rm fuel}$	0.13-1	0.19–1	0.08 - 1	0.22 - 1
$X_{O_2}$	0.1-1	0.26–1	0.16-0.66	0.28 - 0.48
S	0.27 - 10.58	0.14-4.99	0.83-28.98	0.06-0.36
$D_0 ({\rm mm^2/s})$	17.87-19.87	17.98-19.85	13.25-14.93	12.73-15.00
$T_{\rm f}$ (K)	1587-2227	1605-2212	1563-1990	1733-2085
$T_{\rm ad}$ (K)	2050-2920	2080-2900	2019-2600	2257-2753
$\dot{m}_{\rm bur}  ({\rm mg/s})$	0.35-4.39	4.02–9.01	0.46-4.57	3.62-6.05
L <sub>st,meas</sub> (mm)	6.4-60.9	6.02–45	11.3-64.1	6.1–16.3



Fig. 6. Flame length measurements compared to the extended Roper model predictions for (a) methane and (b) propane. Previous results are also shown, but are not included in the determinations of  $R^2$ .

flame temperatures, burner gas flow rates, and measured stoichiometric lengths ( $L_{st,meas}$ ). The propane NDFs have a narrower range of  $X_{O_2}$  than those of methane, owing to soot interference. Figure 5 shows the reactant concentrations for which Refs. [2,5,36] measured  $L_{st}$ , and these span a much smaller range.

Parameter  $\alpha$  from Eq. (4) was optimized by maximizing the coefficient of determination in plots of modeled versus measured  $L_{st}$ . Its optimized value was found to be  $\alpha = 0.735$ , which is within the range of 0.3–1 found previously for fuel/air NDFs and IDFs [27,28].

The ranges of  $D_o$  and  $T_f$  are shown in Table 2. For all these flames  $D_o$  is lower than the Roper et al. [31] value of 20 mm<sup>2</sup>/s, and  $T_f$  is higher than their value of 1500 K. For the present test matrix, Q and S are the key factors in predicting  $L_{st}$ . This is because they vary much more widely than do  $D_0$  and  $T_f$  (see Table 2). Thus, at constant burner reactant flow rate, diluent addition increases  $L_{st}$  primarily by changing Q and/or S, although  $T_f$  and  $D_o$  also contribute.

The measured flame lengths are compared with the extended Roper model predictions in Fig. 6. The predictions generally agree with the measurements, with  $R^2$  coefficients of determination of 0.87 and 0.97 for methane and propane. The scatter in these plots is attributed to experimental error and the assumptions made by the Roper model.

The original model of Roper et al. [31] (predicated on  $T_f = 1500 \text{ K}$ ,  $T_0 = 293 \text{ K}$ , and  $D_0 = 20 \text{ mm}^2/\text{s}$ ), which is not plotted here, yields correlations with  $R^2$  of 0.83 and 0.85 for methane and propane. This difference is small for methane, which was the fuel used most in the Roper et al. [31] tests, but is significant for propane. Evidently the original Roper model is valid for methane NDFs and IDFs with nitrogen dilution, but the extended model is more robust for fuels like propane with diffusivities different from methane's.

The extended Roper model predicts stoichiometric lengths best when the fuel and oxygen mole fractions are between 0.3–0.7, but it overestimates (and underestimates) lengths at higher (and lower) reactant mole fractions. Consistent with this, the measurements of Refs. [2,5,32,36] are above the fits in Fig. 6 and those of Ref. [27] are generally below the fit. These trends arise because the Roper model does not account for radiative losses (e.g., by decreasing  $T_f$ ), which generally increase with increasing reactant mole fractions.

#### Conclusions

The stoichiometric lengths of 174 normal and 113 inverse jet diffusion flames were measured. The ranges of conditions were as wide as possible, and far wider than in past work. Reactant dilution increased the stoichiometric lengths of both NDFs and IDFs when burner reactant flow rate was constant, although this effect was small for high reactant mole fractions. This counters past assertions that inert addition to the burner reactant has a negligible effect on flame length.

The analytical model of Roper for stoichiometric flame length predictions was found to hold for normal and inverse diffusion flames over a wide range of conditions. An improved property model is proposed to improve generality and accuracy, especially for fuels with diffusivities different from methane's. The characteristic diffusivity of the gas mixture was taken to be the average diffusivity of the fuel and oxygen into the stoichiometric products. The characteristic temperature was set empirically to 0.735 times the adiabatic temperature plus 0.265 times the ambient temperature, which is the only calibration factor used in the model. The extended Roper model reproduces the measured lengths reasonably well.

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